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TITLE OF THE INVENTION

A METHOD AND A SYSTEM FOR SPEED CONTROL OF A ROTATING ELECTRICAL MACHINE WITH FLUX COMPOSED OF TWO QUANTITIES

CROSS REFERENCE TO RELATED PATENT DOCUMENTS

The present document is based on published international patent application No. WO 99/29034, the entire contents of which being incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a system and a method for the adaptation, optimization, and/or control of the speed of a rotating electric machine intended to be directly connected to a distribution or transmission network.

Discussion of the Background:

The rotating electric machine which occurs in the present invention may be, for example, a synchronous machine, an asynchronous machine, a double-fed machine, an asynchronous converter cascade, an external pole machine or a synchronous flux machine.

To connect machines of this kind to distribution or transmission networks, hitherto transformers have been used for step-up transformation of the voltage to network level, that is, to the range of 130-400 kV.

Generators with a rated voltage of up to 36 kV are described by Paul R. Siedler, "36 kV Generators Arise from Insulation Research", Electrical World, 15 October 1932, pages 524-537. These generators have windings of high-voltage cable, wherein the insulation is divided into different layers with different dielectric constants. The insulating mate-

rial used is commonly formed of different combinations of three components, namely, mica, foil-mica, varnish, and paper.

Now, it has been shown that by manufacturing windings of a machine using an insulated electric high-voltage conductor with a solid insulation such as used in cables for power transmission, the voltage of the machine may be increased to levels such that the machine may be directly connected to any power network without intermediate transformers. A typical operating range for these machines is 30-800 kV.

The insulated conductor or high-voltage cable which is used in the present invention is flexible and of the kind described in more detail in PCT applications SE97/00874 (WO 97/45919) and SE97/00875 (WO 97/45847). A further description of the insulated conductor or cable is to be found in PCT-applications SE97/00901 (WO 97/45918), SE97/00902 (WO 97/45930) and SE97/00903 (WO 97/45931).

In the device according to the invention, the windings are preferably of a kind corresponding to cables with a solid extruded insulation which are currently used for power distribution, for example so-called XLPE cables or cables with EPR insulation. Such a cable has an inner conductor composed of one or more strands, an inner semiconductor layer surrounding the conductor, a solid insulating layer surrounding the semiconducting layer, and an outer semiconducting layer surrounding the insulating layer. Such cables are flexible, which is an important property in this context since the technology for the device according to the invention is primarily based on a winding system where the winding is made with wires which are drawn back and forth a plurality of turns, that is, without joints in the coil ends which are required when the winding in the core contains stiff conductors. An XLPE cable normally has a flexibility corresponding to a radius of curvature of about 20 cm for a cable with a diameter of 30 mm and a radius of curvature of about 65 cm for a cable with a diameter of 80 cm. The expression “flexible” in this context thus indicates that the winding is flexible down to a radius of curvature in the order of magnitude of 8-25 times the cable diameter.

The winding should be made such that it may maintain its properties also when being bent and when, during operation, it is subjected to thermal stresses. It is of great importance in this connection that the layers maintain their adhesion to one another. Of decisive importance in this connection are the material properties of the layers, above all their elasticities and their relative coefficients of thermal expansion. For an XLPE cable, for ex-

ample, the insulating layer is of crosslinked low-density polyethylene and the semiconducting layers of polyethylene with soot and metal particles mixed thereinto. Volume changes as a result of temperature variations are absorbed entirely as changes in radius in the cable, and because of the comparatively slight difference in the coefficients of thermal expansion of the layers in relation to the elasticities of these materials, the radial expansion of the cable will be able to take place without the layers loosening or delamninating from each other.

The material combinations described above are only to be considered as examples. The scope of the invention of course also includes other combinations which fulfil the conditions mentioned and which fulfil the conditions of being semiconducting, that is, with a mass resistivity in the range $1\text{-}10^5$ Ω–cm, and of being insulating, that is, with a mass resistivity greater than 10^5 Ω–cm, respectively.

The insulating layer may, for example, be formed in whole or in part of a solid thermoplastic material such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethyl pentene (PMP), crosslinked materials such as crosslinked polyethylene (XLPE) or rubber, such as ethylene-propylene rubber (EPR) or silicone rubber.

The inner and outer semiconducting layers may have the same base materials but mixed with particles of conducting materials, such as soot or metal powder.

The mechanical properties of these materials, primarily their coefficients of thermal expansion, are influenced to a rather slight extent by whether they are mixed with soot or metal powder or not. The insulating layer and the semiconducting layers will thus have substantially the same coefficients of thermal expansion.

For the semiconducting layers, also ethylene vinyl acetate copolymer/nitrile rubber, butyl-grafted polyethylene, ethylene acrylate copolymer, ethylene ethyl acrylate copolymer and ethylene butyl acrylate copolymer may constitute suitable polymers.

Also when different layers of materials are used as a base in the respective layers, it is desirable for their coefficients of thermal expansion to be of the same order of magnitude. This is true of the combination of the materials listed above.

The materials listed above have quite a good elasticity which is sufficient for any minor deviations in the coefficients of thermal expansion of the materials in the layers to

be taken up in the radial direction of the elasticity such that cracks or other damage do not arise and such that the layers do not become detached from each other.

The conductivity of the two semiconducting layers is sufficiently great to substantially equalize the potential along the respective layer. At the same time, the conductivity is so low that the outer semiconducting layer has sufficient resistivity to enclose or contain the electric field in the cable.

Each of the two semiconducting layers thus essentially constitutes an equipotential surface and the winding with these layers will substantially enclose the electric field within it.

It is, of course, not excluded that one or several further semiconducting layers may be arranged in the insulating layer.

It is previously known to achieve a more efficient and flexible operation of hydroelectric power stations/pump storage plants with, for example, VARSPEED generators, and that each turbine has an optimum working point, at which speed net head and water flow are adapted to one another to give maximum efficiency. For large machines, the speed may be controlled in several ways, for example by pole switching, stator supply and frequency adaptation through the use of frequency converters or of a sub- and supersynchronous converter cascade which feeds an asynchronous machine from two directions, that is, both via a stator and a rotor. The rotating three-phase rotor winding and the stationary frequency converter equipment for control of the rotor flux and hence the slip frequency for speed optimization take place via slip rings.

Use of slip rings in speed optimization entails a number of disadvantages such as wear, fouling and hence increased maintenance costs.

SUMMARY OF THE INVENTION

The object of the present invention is to solve the above-mentioned problems. This is achieved with a system for adaptation/optimization of the speed of a rotating electric machine included in the system and with a method for speed control of a rotating electric machine as described herein. The machine included in the system according to a first embodiment of the present invention has at least two electric windings, each of which is formed from at least one electric conductor, a first semiconducting layer arranged surrounding the conductor, an insulating layer arranged surrounding the first semiconducting

layer, and a second semiconducting layer arranged surrounding the insulating layer. In addition, the system has mechanisms which generate the resultant stator and air gap flux of the machine during operation, where the flux is composed of at least two vectorial quantities.

One advantage of the system according to the present invention is that no slip rings occur, which, inter alia, entails simplified maintenance and no losses as a result of brush voltage drop. In addition, a rapid demagnetization in case of fault may be obtained.

An advantageous embodiment of the system is obtained in accordance with the invention in that the potential of the first semiconducting layer is essentially equal to the potential of the conductor.

In connection therewith, it is an advantage if the second semiconducting layer is arranged to form essentially an equipotential surface, surrounding the conductor.

An additional advantage in this connection is obtained if the second semiconducting layer is connected to a predetermined potential.

In connection therewith, it is an advantage if the predetermined potential is ground potential.

A further advantage in connection therewith is obtained if at least two adjacent layers of the windings of the machine have essentially equal coefficients of thermal expansion.

In connection therewith, it is an advantage if the conductor has a number of strands, of which at least some are in electric contact with one another.

A further advantage in connection therewith is obtained if each one of the three layers mentioned is secured to adjacent layers along essentially the whole contact surface.

According to a second embodiment of the system according to the invention, the machine included in the system includes at least two electric winding, each of which is formed from a high-voltage cable having one or more current-carrying conductors, each conductor exhibiting a number of strands, a first semiconducting layer arranged around each conductor, an insulating layer of solid insulating material arranged around the first semiconducting layer, and a second semiconducting layer arranged around the insulating layer. In addition, the system has a mechanism which generates the resultant stator and air gap flux of the machine in operation, which flux is composed of at least two vectorial quantities.

One advantage of the system according to the second embodiment of the present invention is that no slip rings occur, which, inter alia, entails simplified maintenance and no losses as a result of brush voltage drop. In addition, a rapid demagnetization in case of fault may be obtained.

An additional advantage in connection therewith is obtained if the insulating conductor or the high-voltage cable is flexible.

In connection therewith, it is an advantage if the layers are arranged to adhere to one another even if the insulating conductor or the high-voltage cable is bent.

An additional advantage in connection therewith is that the flux-generating member has an extra winding arranged on the machine and magnetization equipment connected to the machine, whereby one flux vector is generated via the extra winding and the magnetization equipment and one flux vector is generated via the ordinary winding of the machine.

In connection therewith, it is an advantage if the magnetization equipment contains a first frequency converter.

An additional advantage in this connection is obtained if the system furthermore has an auxiliary feeder connected to the first frequency converter and the machine.

In connection therewith, it is an advantage if the machine is formed from an asynchronous rotor, and if the auxiliary feeder has a stator winding and a permanent-magnet rotor connected to the asynchronous rotor.

An additional advantage in connection therewith is obtained if the system furthermore has a transformer connected to the first frequency converter and the auxiliary feeder, where the transformer is connected to a distribution busbar via a first circuit breaker, and a second frequency converter connected to the transformer, where the second frequency converter is connected to the distribution busbar via a second circuit breaker.

In connection therewith, it is an advantage if the windings are flexible and if the mentioned layers make contact with one another.

An additional advantage in this connection is if the mentioned layers are of materials with such elasticities and such a relation between the coefficients of thermal expansion of the materials that the volume changes of the layers, caused by temperature variations during operation, are capable of being absorbed by the elasticity of the materials such

that the layers remain in contact with one another at the temperature variations which occur during operation.

In connection therewith, it is an advantage if the materials in the layers mentioned have a high elasticity.

An additional advantage in connection therewith is obtained if each semiconducting layer constitutes essentially an equipotential surface.

The method according to a first embodiment of the present invention for speed control of a rotating electric machine is applicable to a machine which is intended to be directly connected to a distribution or transmission network. The machine is formed from at least two electric windings, each of which has at least one electric conductor, a first semiconducting layer arranged surrounding the conductor, an insulating layer arranged surrounding the first semiconducting layer, and a second semiconducting layer arranged surrounding the insulating layer. The method includes the step of generating at least two vectorial quantities which constitute the resultant stator and air gap flux of the machine during operation.

The method according to a second embodiment of the present invention for speed control of a rotating electric machine is applicable to a machine which is intended to be directly connected to a distribution or transmission network. The machine has at least two electric windings, which are each formed from a high-voltage cable having one or more current-carrying conductors, whereby each conductor exhibits a number of strands, a first semiconducting layer arranged around each conductor, an insulating layer of solid insulating material arranged around the first semiconducting layer, and a second semiconducting layer arranged around the insulating layer. The method includes the step of generating at least two vectorial quantities which constitute the resultant stator and air gap flux of the machine during operation.

An advantage of the method according to the two embodiments of the present invention is that no slip rings occur, which, inter alia, entails simplified maintenance and no losses as a result of brush voltage drop. In addition, a rapid demagnetization in case of fault may be obtained.

In connection therewith, an advantage is obtained if the method includes the following additional step:

- controlling at least one of the vectorial fluxes with respect to phase position as well as amplitude and speed of rotation relative to the flux generated and rotated by the connecting network.

A further advantage in connection therewith is obtained if the method includes the following steps:

- generating a flux vector via an extra winding, mounted on the stator of the machine, and magnetization equipment connected to the machine, and
- generating a flux vector via the ordinary winding of the machine.

According to a first aspect of the invention, the rotating electric machine additionally includes an asynchronous rotor, whereby the flux control is used for speed-control of the machine in generator operating mode.

According to a second aspect of the invention, the rotating electric machine additionally includes an asynchronous rotor, whereby the flux control is used for speed-control of the machine in motor operating mode.

According to a third aspect of the present invention, the flux control is used to suppress the harmonic content of the stator voltage in the ordinary stator winding of the machine.

According to a fourth aspect of the present invention, the reactive magnetization current of the machine is injected via the extra winding, which makes possible control of the voltage of the machine on the ordinary winding of the machine both for a non-mains-connected and a mains-connected machine.

In connection therewith, it is an advantage if the rotating electric machine furthermore includes a permanent-magnet rotor, connected to the asynchronous rotor, for generating magnetization current and other auxiliary power.

According to a further aspect of the present invention, the flux control is used for interruption-free change from generator operating mode to motor operating mode and vice versa.

In connection therewith, it is an advantage if the resultant flux in the machine is:

$$\Phi = \Phi_1 + \Phi_2$$

where Φ_1 is the rotating flux on the stator side of the machine and Φ_2 is the flux generated by the rotor current, whereby

$$\Phi_1 = \Phi_{1magn} + \Phi_{1stator}$$

where $\Phi_{1stator}$ is the rotating flux generated by the current in the ordinary winding, whereby the speed of rotation on $\Phi_{1stator}$ is dependent on the frequency of the network and the number of pole pairs in the machine, and Φ_{1magn} is the rotating flux generated by the current in the extra winding, which flux is controllable with respect to phase position as well as amplitude and frequency relative to the flux vector of the ordinary winding.

An additional advantage in connection therewith is obtained if the vectorially created flux in the machine is controlled with the aid of the relative phase position as well as the relative amplitude value between the active and reactive current values of the ordinary winding (54) and the extra winding (56).

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be explained in greater detail by the following description of preferred embodiments of the invention with reference to the accompanying drawings.

Figure 1 is a cross-section view of a high-voltage cable;

Figure 2 is a diagram which shows a system according to the present invention for adaptation/optimization of the speed of a rotating electric machine included in the system;

Figures 3a and 3b are schematic figures which more clearly show the solution on principle for the system shown in Figure 2;

Figures 4a and 4b are schematic figures which for the purpose of clarification show, respectively, the rotating fluxes and the electromotive force (EMF) induced in the rotor part in the system shown in Figure 2;

Figures 5a, 5b and 5c are three diagrams which illustrate the principle of control/change of the speed of rotation for the resultant flux in the machine in the system shown in Figure 2; and

Figure 6 is a flow diagram of the method according to the present invention for speed control of a rotating electric machine.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 shows a cross-section view of a high-voltage cable 10 which is traditionally used for transmission of electric power. The high-voltage cable 10 shown may, for ex-

ample, be a standard XLPE cable 145 kV but without a sheath of screen. The high-voltage cable 10 has an electric conductor, which may have one or more strands 12 of circular cross section of, for example, copper (Cu). These strands 12 are arranged in the centre of the high-voltage cable 10. Around the strands 12 there is a first semiconducting layer 14. Around the first semiconducting layer 14 there is an insulating layer 16, for example XLPE insulation. Around the insulating layer 16 there is a second semiconducting layer 18. In the high-voltage cable 10 shown, the three layers 14, 16, 18 are designed so as to adhere to one another also when the cable 10 is bent. The shown cable 10 is flexible and this property is retained in the cable 10 during its service life.

Figure 2 shows a diagram of a system according to the present invention for adaptation/optimization of the speed of a rotating electric machine included in the system. The system 20 includes a rotating electric machine 22, which is directly connected to a distribution or transmission network 24. The rotating electric machine 24 has at least two windings, wherein each winding in a first embodiment of the present invention contains at least one conductor, a first semiconducting layer arranged surrounding the conductor, an insulating layer arranged surrounding the first semiconducting layer, and a second semiconducting layer arranged surrounding the insulating layer. According to a second embodiment of the system 20 according to the present invention, the windings are each formed from the high-voltage cable 10 shown in Figure 1. The system 20 additionally has a member 26 which generates the resultant stator and air gap flux of the machine in operation, which flux is composed of at least two vectorial quantities. In addition, the system 20 contains magnetization equipment 28, connected to the rotating electric machine 22, which in the shown example is in the form of a first frequency converter 28. Connected to the rotating electric machine 22 is an auxiliary feeder 30. In addition, the system 20 has a transformer 32 for voltage adaptation, connected to the first frequency converter 28 and the auxiliary feeder 30. The transformer 32, in its turn, is connected to a distribution busbar 36 via a first circuit breaker 34. In addition, the system 20 has a second frequency converter 38 for auxiliary power generation, which second frequency converter 38 is connected, on the one hand, to the transformer 32 and, on the other hand, to the distribution busbar 36 via a second circuit breaker 40.

Figures 3a and 3b schematically show the solution on principle for the system 20 shown in Figure 2. Figure 3a shows the rotor 50 and the stator 52, respectively, of the ro-

tating electric machine 22. The stator 52 is provided in traditional manner with a three-phase winding 54, also called ordinary winding 54 or main winding 54. In addition, the stator 52 is provided with an extra winding 56. When the rotating electric machine 22 is in operation, a rotating flux Φ_1, among other things, is generated on the stator side, which flux Φ_1 rotates in the direction of the dotted arrow. Figure 3b shows a part of the system 20 shown in Figure 2 which is of importance to the present invention. Again, the main winding 54 (three-phase) and the extra winding 56 (three-phase) of the stator are shown, the extra winding 56 being connected to the first frequency converter 28. In addition, the stator winding 58 (three-phase) of the auxiliary feeder 30 (cf. Fig. 2) is shown, which is also connected to the first frequency converter 28. The rotating electric machine 22 (cf. Fig. 2) additionally includes an asynchronous rotor 60 for the main winding 54 and the extra winding 56 of the stator. In addition, Figure 3b shows a permanent-magnet rotor 62 included in the auxiliary feeder 30 (cf. Fig. 2). The permanent-magnet rotor 62 is connected to the asynchronous rotor 60 so that these rotate together. The system 20 may be used for adaptation/optimization of the speed of a rotating electric machine 22 included in the system 20. This is achieved by composing the rotating flux Φ_1 on the stator side 52 (cf. Fig. 3) from at least two flux vectors. One flux vector is generated in traditional manner via the main winding 54 of the stator 52 and one flux vector is generated via the extra winding 56 of the stator 52 and the first frequency converter 28. By controlling the flux vector, generated via the extra winding 56 and the first frequency converter 28, with respect to phase position as well as amplitude and frequency relative to the flux vector generated via the main winding 54, the angular velocity of the total flux vector may rotate both supersynchronously and subsynchronously related to the flux vector generated via the main winding.

Figures 4a and 4b schematically show the rotating fluxes and the EMF induced in the rotor part, respectively, in the system shown in Figure 2. Figure 4a again shows parts of the rotating electric machine 22 (cf. Fig. 2) in the form of the rotor 50 and the stator 52. As is also clear from Figure 3a, the stator 52 is provided with a main winding 54 and an extra winding 56. The rotor 50 rotates in the direction of the arrow A. The rotating total flux Φ_1 of the stator 52 rotates in the direction of the arrow B with the speed $n_{\Phi 1}$. The total generated flux for the machine 22 in operation is

$$\Phi = \Phi_1 + \Phi_2$$

where Φ_1 is the rotating flux on the stator side, and Φ_2 is the flux generated by the rotor current. The rotating flux Φ_1 on the stator side may be expressed as follows

$$\Phi_1 = \Phi_{1magn} + \Phi_{1stator}$$

where $\Phi_{1stator}$ is the rotating flux generated by the current in the main winding 54, and Φ_{1magn} is rotating and controllable flux. Φ_{1magn} is generated via the extra winding 56 of the stator 52 and the first frequency converter 28. Figure 4b schematically shows the rotor 50. The rotating air gap flux induces a winding EMF, e_{rotor}, in the rotor winding. The rotor current, I_{rotor}, driven by the EMF e_{rotor} gives rise to a torque Mv. The winding EMF e_{rotor} may be expressed as

$$e_{rotor} = k1 \times \Phi_1 \times (n_{rotor} - n_{\Phi 1})$$

The torque may be expressed as

$$Mv = k2 \times \Phi_1 \times I_{rotor}$$

where k1, k2 are constants, n_{rotor} is the speed of the rotor 50, which may be changed and adapted for optimization of, for example, the efficiency of the turbine, and $n_{\Phi 1}$ is the speed of the rotating flux Φ_1 on the stator side, whereby the speed $n_{\Phi 1}$ may be changed and adapted for slip optimization.

Figures 5a, 5b and 5c show three different diagrams which illustrate the principle of control/change of the speed of rotation for the resultant flux Φ_1 on the stator side in the machine 22 in the system 20 shown in Figure 2. Figure 5a shows how $\Phi_{1stator}$ varies with the time t. The speed of rotation of $\Phi_{1stator}$ depends on the frequency of the network (cf. Fig. 2) and the number of pole pairs in the rotating electric machine 22. Figure 5b shows how Φ_{1magn} varies with the time t. The amplitude, frequency and phase position of Φ_{1magn} are determined with respect to the desired speed of rotation of Φ_1. Figure 5c shows how the resultant rotating flux Φ_1 in the stator 52 varies with the time t.

Figure 6 shows a flow diagram of the method according to the present invention for speed control of a rotating electric machine. The method according to the present invention includes a number of steps which will be described below. The flow diagram starts at block 70. The next step, at block 72, includes starting and connecting the rotating electric machine 22 to the network (cf. Fig. 2). Thereafter, at block 74, at least two vectorial quantities are generated, which constitute the resultant stator and air gap flux of the machine in operation. Provided that there are two vectorial quantities, one flux vector $\Phi_{1stator}$ is

generated via the main winding 54 of the stator 52, and one flux vector Φ_{1magn} is generated via the extra winding 56 of the stator 52 and the first frequency converter 28. Thereafter, at block 76, it is inquired whether the speed of the machine is suitable. If the question is answered in the affirmative, block 76 is reiterated. On the other hand, if the answer is negative, the method continues to block 78. In block 78, the step of controlling at least one of the vectorial fluxes with respect to phase position as well as amplitude and frequency (speed of rotation) relative to the flux generated and rotated by the connecting network is carried out. This control implies that the machine has the desired/appropriate speed. Thereafter, at block 80, it is inquired whether the machine is to be in operation. If the question is answered in the affirmative, block 76 is reiterated. On the other hand, if the answer is negative, the method continues to block 82. At block 82, the operation of the machine is stopped. At block 84, the method is terminated.

The invention is not limited to the embodiments shown but several modifications are feasible within the scope of the inventive concept. Thus adaptation of the slip frequency may take place both during motor and generator operation and by suitable dimensioning of the frequency converter equipment, all operating modes may, in principle, be met.

In addition, the principle may be applied to rapid, interruption-free change from motor operation to generator operation in, for example, industrial applications.

Further, the principle may be applied to reduction/elimination of the harmonic content in the stator voltage of a machine. The principle may be applied to both synchronous and asynchronous machines.

In addition, the frequency converter equipment and the extra winding of the stator may be used both when starting the machine upon start-up and when braking the machine upon shutdown.

Further, the angular velocity of the flux vector generated via the extra winding is controllable via the stationary frequency converter equipment and hence an optimum operating position for adaptation to a changed turbine speed caused by changed net head may always occur.

In addition, the vectorially created flux in the machine may be controlled with the aid of the relative phase position as well as the relative amplitude position between the active and reactive current values of the ordinary winding and the extra winding.

The invention is not limited to the embodiments shown, but several variants are feasible within the scope of the appended claims.